

## Surface Wave Processes on the Continental Shelf and Beach

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### LONG-TERM GOAL

There is a growing need for surface wave information on the continental shelf and beach to estimate sea state, and to provide input for models of currents, sediment transport, radar backscatter and aerosol generation. While surface wave spectra in the open ocean evolve slowly over distances of  $O(100\text{-}1000\text{ km})$ , wave properties on the continental shelf and beach are highly variable (typical length scales of  $0.1\text{-}10\text{ km}$ ) owing to a variety of topographic effects (e.g., shoaling, refraction, scattering) and strongly enhanced nonlinear interactions and dissipation. The long-term goal of this research is to develop a better understanding of the physical processes that affect the generation, propagation and dissipation of surface waves in shallow coastal waters, and improve the accuracy of models that predict the transformation of wave properties across the shelf and beach.

### OBJECTIVES

- ◆ predict accurately the nonlinear shoaling transformation of waves over a gently sloping beach
- ◆ predict accurately the nonlinear transfer of energy from wind waves to lower-frequency infragravity waves and the subsequent propagation and damping of these waves on the continental shelf
- ◆ determine the effects of refraction and bottom friction on the propagation of swell across a wide continental shelf
- ◆ determine the importance of resonant quartet interactions in the evolution of wind wave spectra on the continental shelf
- ◆ improve the representation of nonlinear wave-wave interactions in operational wave prediction models
- ◆ determine the effects of wave nonlinearity and directional spreading on sea surface statistics

### APPROACH

A combination of theory, analytical and numerical models, and field experiments is used to investigate the physical processes that affect surface wave properties on the continental shelf and beach. The transformation of wave spectra across the continental shelf is predicted with models based on a

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spectral energy balance that include the effects of refraction and resonant quartet interactions. On beaches near-resonant triad interactions cause strong evolution of wave spectra over distances of only a few wavelengths. A new stochastic shoaling model is under development, based on the Boussinesq equations for weakly nonlinear, weakly dispersive waves, that can be applied to random, directionally spread wind waves propagating over a gently sloping beach with approximately straight and parallel depth contours. While the wind waves and associated high-frequency harmonics are mostly dissipated in the surf zone, the nonlinearly excited infragravity waves reflect from the beach and radiate seaward across the shelf as free waves. A spectral WKB approximation is used to describe the refraction and topographic trapping of infragravity waves radiated from shore.

Extensive field data are used to verify predictions of topographic and nonlinear effects, and to estimate the energy losses owing to bottom friction and wave breaking. The data sets include coherent arrays of pressure sensors and current meters deployed near Duck, NC, Cape Canaveral, FL, Norfolk, VA, and Point Conception, CA, and single point wave measurements (pressure sensors and directional buoys) from numerous field sites. Analysis techniques applied to the measurements include various inverse methods to extract directional and wavenumber properties from array cross-spectra, bispectral and trispectral analysis to detect nonlinear coupling, as well as standard statistical methods to determine empirical relationships between observed variables.

## WORK COMPLETED

Detailed field observations of waves shoaling on the inner continental shelf and beach were collected near Duck, NC, in the SandyDuck experiment. A coherent array of 9 pressure sensors and a directional wave buoy were deployed in 20-m depth, 5-km from shore. A more extensive array of 56 pressure sensors, 36 current meters, and 33 sonar altimeters was deployed between the shoreline and 5-m depth (a collaborative experiment led by S. Elgar). High quality data were collected nearly continuously during a 4-month period (August-November 1997).

A new stochastic wave shoaling model was developed based on a third-order statistical closure of Boussinesq equations (Herbers and Burton, 1997). The model consists of a coupled set of evolution equations for the wave spectrum and bispectrum that smoothly matches (in the limit of weak nonlinearity) the steady bispectrum solution of dispersive waves in finite depth (Hasselmann et al., 1963). A one-dimensional version of the model for unidirectional waves was validated through comparisons with field data from a cross-shore transect of pressure sensors collected by S. Elgar and R. T. Guza in the DUCK94 experiment. A two-dimensional implementation for directionally spread waves was completed and will be tested with the extensive directional wave measurements collected in the SandyDuck Experiment.

The effects of wave breaking on the directional properties of shoaling waves were investigated with measurements from a cross-shore array of bi-directional current meters deployed by R. T. Guza and S. Elgar in the DUCK94 experiment. In benign conditions when most of the instruments were outside the surfzone, the observations show a decrease in directional spreading of wave energy toward the shore that is consistent with refraction toward normal incidence and nonlinear energy transfers to wave components that propagate in approximately the same direction as the incident waves. In energetic conditions with wave breaking on a shallow sandbar, the observed directional spreading of wave energy increases sharply in the surf zone. The dramatic directional broadening may have important implications for wave-driven longshore currents and sediment transport.

## RESULTS

The evolution of swell across a wide continental shelf was investigated with measurements from a transect of ten bottom pressure transducers, deployed on the North Carolina shelf during the DUCK94 Experiment (T. H. C. Herbers, E. J. Hendrickson, and W. C. O'Reilly, manuscript in preparation). The results of this study generally show weak variations in swell energy across the shelf during benign conditions, in qualitative agreement with predictions of an energy conserving spectral refraction model. However, large energy losses across the shelf (up to about 70 %) were observed when incident swell energy levels were higher, but not high enough to cause steepness-limited wave breaking (Figure 1). This strong attenuation is likely the result of energy losses in the bottom boundary layer. The observed damping rates are comparable to those reported by Young and Gorman (1995) on the southern coast of Australia, and suggest significantly larger bottom friction factors than are commonly used in wave prediction models.

Figure 1. Decay of energetic swell (offshore significant height 2.5 m) across the North Carolina continental shelf observed in light wind conditions on 19 October, 1994. Circles indicate swell variances observed with a cross-shelf transect of seafloor pressure sensors. Asterisks indicate the swell variances predicted at the same locations with an energy conserving spectral refraction model. Large differences between observed and predicted swell variances suggest strong attenuation of swell through bottom boundary layer processes.

Direct estimates of the contribution of nonlinear wave-wave interactions to the spectral energy balance of breaking waves on a barred beach were obtained from measured wave spectra and bispectra based on a stochastic formulation of Boussinesq equations (T. H. C. Herbers, N. R. Russnogle, and S. Elgar, manuscript submitted for publication in the *J. Phys. Oceanogr.*). The main result of this analysis a surprisingly close balance between energy losses in the energetic part of the spectrum and nonlinear energy transfers to higher frequencies (Figure 2). These observations show that the spectral evolution in the surf zone is strongly controlled by nonlinear triad interactions while dissipation appears to be confined to the high-frequency tail of the spectrum, qualitatively consistent with earlier modeling studies (e.g., Chen et al., 1997, and references therein).

Figure 2. Spectral energy balance observed in the surf zone during DUCK94 at the height of a strong nor'easter event (4 September, 1994; offshore significant wave height 3 m). The upper panel indicates the spectral decay over the sand bar (green=seaward of the bar crest, black=on the bar crest, and magenta=inshore of the bar crest). In the bottom panel estimates of the cross-shore energy flux gradient  $F_x$  and the net nonlinear energy transfer  $S_{nl}$  (both functions of frequency  $f$ ) are compared at the crest of the sand bar (depth 2 m) where the largest energy losses occurred. The estimated  $F_x(f)$  and  $S_{nl}(f)$  closely balance in the energetic part of the spectrum, indicating that the observed decay of the spectral peak in the surf zone is primarily the result of nonlinear transfers to higher frequencies where the energy is presumably dissipated.

## IMPACT/APPLICATIONS

The new nonlinear wave shoaling model developed in this project will be used extensively in numerical simulations of the transformation of ocean waves on beaches.

## TRANSITIONS

The results of this research will be used in the ONR Advanced Wave Prediction Program to improve the parameterizations of shallow water effects in operational regional wave prediction models.

## RELATED PROJECTS

Wave-driven nearshore currents are investigated in collaborative efforts led by R. T. Guza (SIO) and S. J. Lentz (WHOI). Observations of shear waves and infragravity waves in the surf zone are analyzed in collaboration with T. C. Lippmann (SIO) and E. B. Thornton (Naval Postgraduate School).

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